Technical Note DOER-C3
May 1999

Evaluation of Dredged Material for Phytoreclamation Suitability

PURPOSE: This technical note serves primarily to describe an approach to evaluating the phytoreclamation alternative for dredged material treatment. This approach falls under the treatment block described as part of a framework for testing and evaluation of dredged material for beneficial uses in Technical Note DOER-C2 (U.S. Army Engineer Waterways Experiment Station (WES) 1998a). This technical note expands the framework to include a phased approach to determine the suitability of a contaminated dredged material for plant-mediated reclamation (phytoreclamation), sometimes termed phytoremediation.

BACKGROUND: In the course of completing its mission of maintaining and improving navigation in waters of the United States, the U.S. Army Corps of Engineers (CE) must annually manage over 300 million cubic meters of dredged material. Five to ten percent of this material is not suitable for unrestricted open-water placement, and increased opposition to open-water placement is beginning to limit this option where any adverse biological effects are possible. Another option for management of dredged material is placement in confined placement facilities (CPF). However, this is quickly becoming a difficult option, since most CPFs are at or approaching design capacity and locations for new CPFs are hard to find. As a result, other means of handling dredged material are needed. Potential uses of dredged material include landfill cover, recreational, industrial brownfield area development, wildlife habitat, manufactured soil for commercial use, etc. In the case of contaminated dredged material, remediation or reduction of contaminant concentrations may be required prior to its ultimate use. Phytoreclamation offers a potentially effective and affordable means of decontamination. However, at present, it is difficult to determine with certainty if it is a viable alternative for treatment of contaminated dredged material without conducting a number of evaluations.

INTRODUCTION: Phytoreclamation or phytoremediation can be defined by three basic processes (Cunningham and Lee 1995):

- Plant extraction is the removal of contaminants from a soil material or water through plant uptake and bioconcentration with possible volatilization by plant respiration and transpiration (Figure 1).
- Degradation is the metabolism and/or degradation by plant processes or plant-associated enzymes, bacteria, and other microflora (Figure 2).
- Stabilization and containment is the in situ immobilization of contaminants by virtue of reducing soil erosion and minimizing uptake of particular contaminants (Figure 3).

Phytoreclamation of contaminated soils has been applied to industrial sites by commercial entities with documented success. It is fast becoming acceptable to the public and in most cases is less expensive than traditional treatment technologies such as incineration, bioslurry composting, etc.

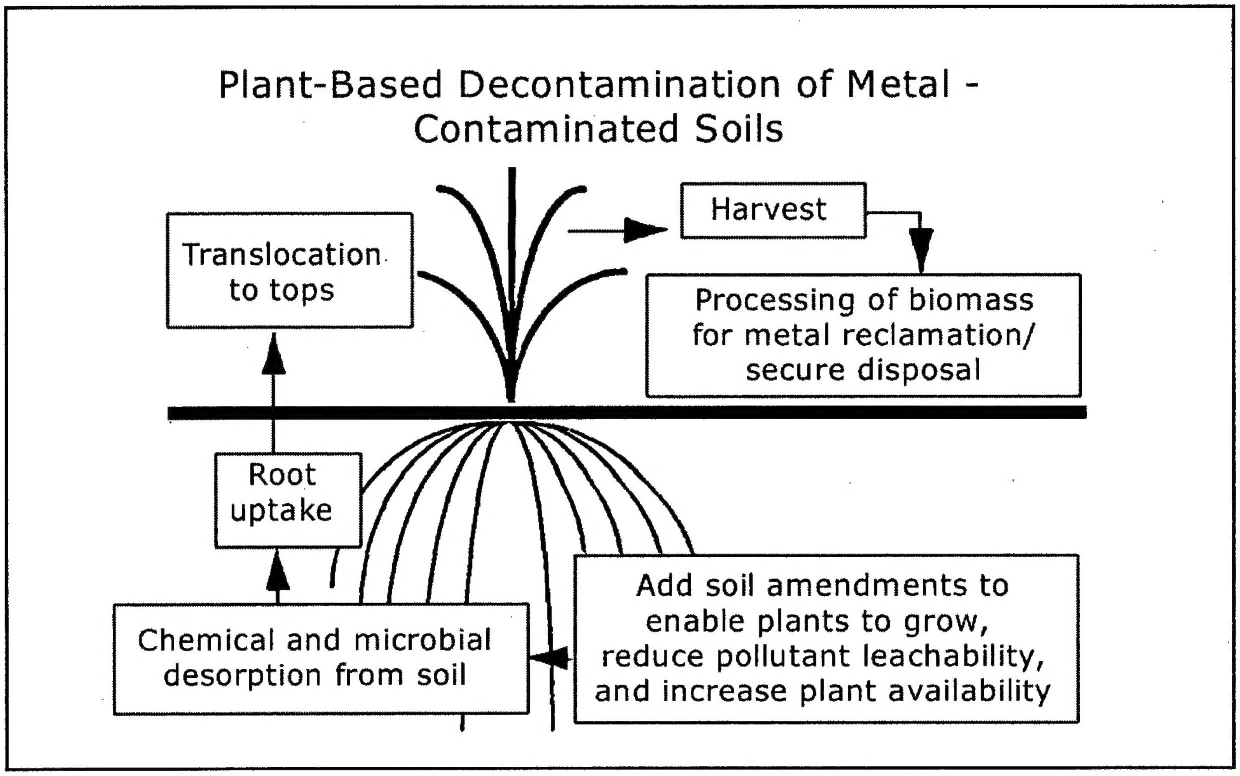

Figure 1. Plant uptake and bioaccumulation processes

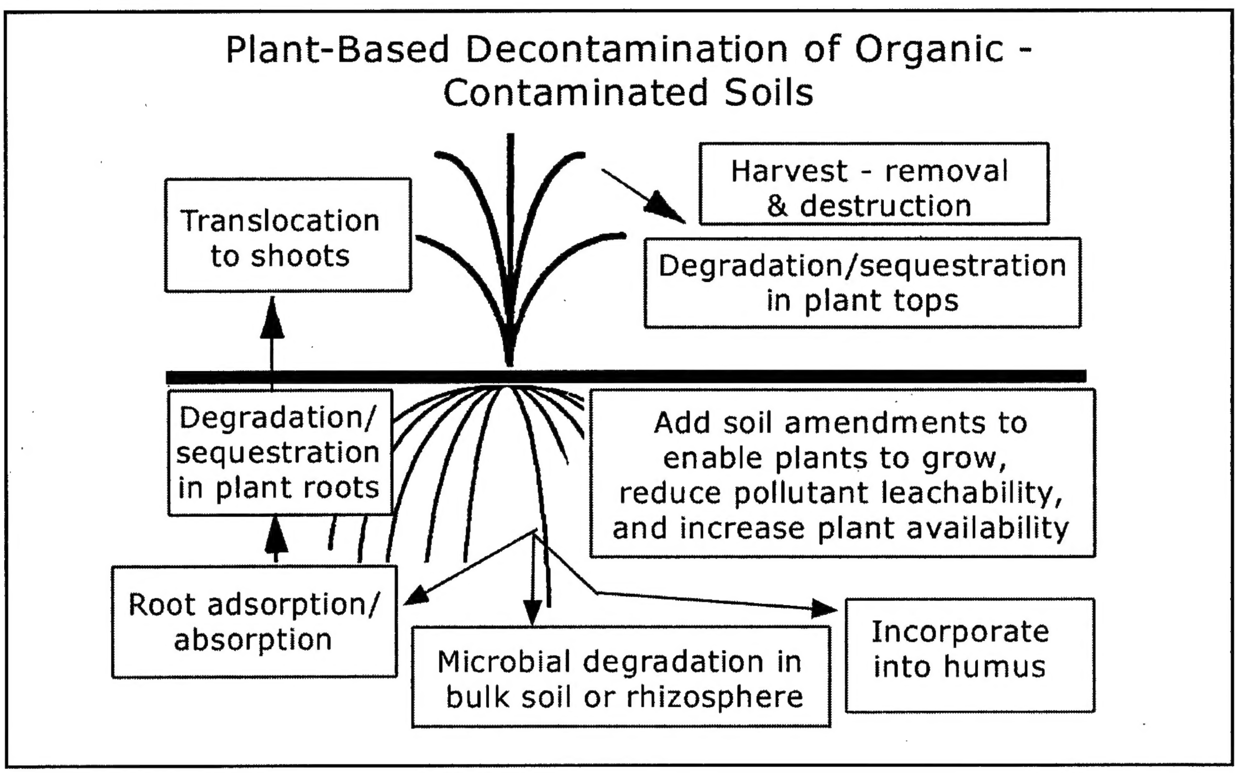

Figure 2. Plant uptake and degradation processes

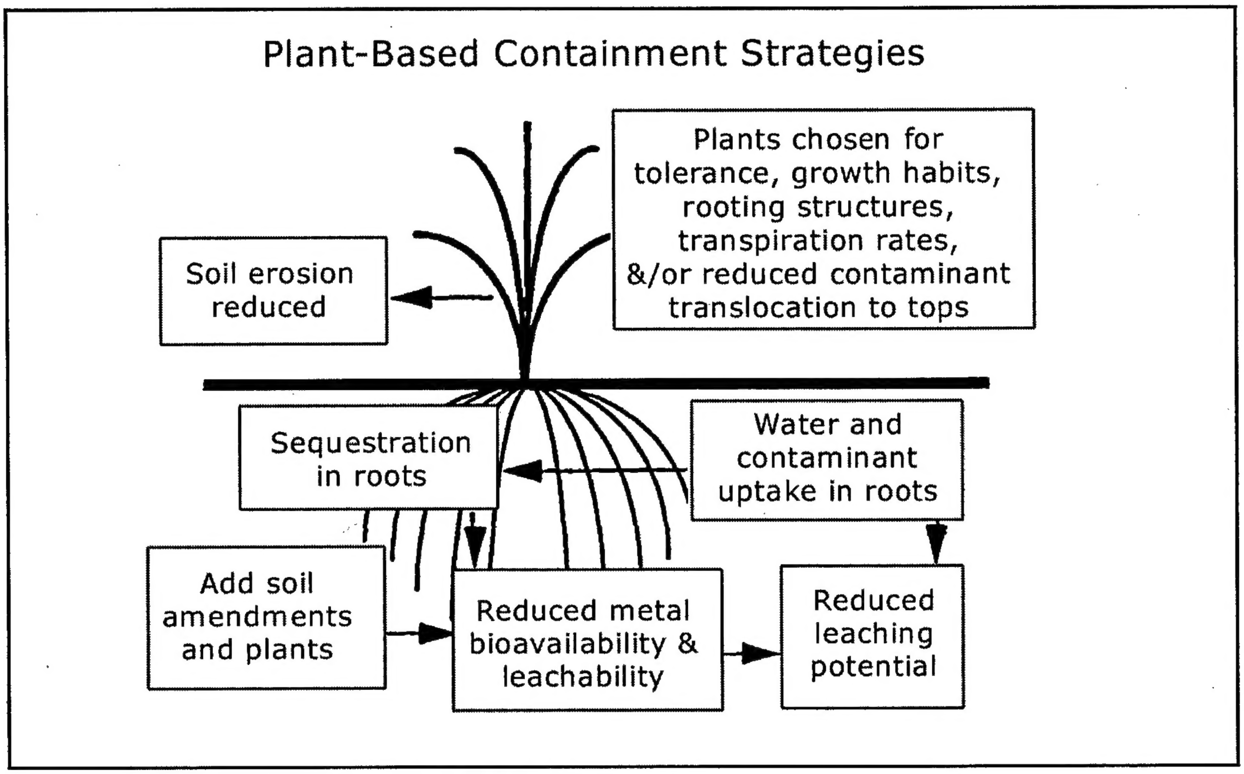

Figure 3. Plant-based containment and stabilitzation processes

For example, the U.S. Army Environmental Center (USAEC) estimated the cost for phytoreclamation of 1 acre of lead-contaminated soil to a depth of 50 cm to be $60,000 to $100,000 compared with excavation and landfilling at a cost of $400,000 to $1,700,000 (USAEC 1997). Also, phytoreclamation has high economic potential for commercial entities that can successfully demonstrate its effectiveness. The CE can benefit from these successes by developing and demonstrating these new and innovative technologies for managing dredged material.

Most industrial cleanup efforts deal with one contaminant or one class of contaminants at a time. This is not the case with most dredged material. Heavy metals, petroleum hydrocarbons, polychlorinated biphenyls, organotins, dioxins, and other contaminants may be present in dredged material. Drastic physicochemical changes may also occur as a dredged material is removed from an anaerobic, aquatic condition and placed in an aerobic, terrestrial environment. This is especially true when the transition is from an aquatic saltwater to an upland freshwater site. All of these conditions must be addressed when considering phytoreclamation as an alternative for cleanup/ stabilization of dredged material contaminants.

Evaluating the potential success of phytoreclamation of dredged material will include three basic assessments including sediment physical and chemical characteristics, plant exposure effects, and contaminant reduction effectiveness. Additionally, site management issues and goals must be considered prior to selection and implementation of a phytoreclamation process. The advantages and disadvantages of various phytoreclamation approaches, as shown for metals in Table 1, may require specific management considerations to implement the process. For example, phytoextraction may increase the bioavailability of some metals to animals such as earthworms that reside in the

Table 1
Types of Phytoreclamation Technology for Metal-Contaminated Soil Materials: Advantages and Disadvantages (U.S. Environmental Protection Agency (EPA) 1996)

Type of Phytoreclamation	Advantages	Disadvantages
Phytoextraction by trees	High biomass production	Potential for offsite migration and leaf transportation of metals to soil surface
	Potential for metal recovery	Metals are concentrated in plant biomass and must be disposed of eventually
Phytoextraction by grasses	High accumulation	Low biomass production and slow growth rate
	Potential for metal recovery	Metals are concentrated in plant biomass and must be disposed of eventually
Phytoextraction by crops	High biomass and increased growth rate	Potential threat to the food chain through ingestion by herbivores
		Metals are concentrated in plant biomass and must be disposed of eventually
Phytostabilization	No placement of contaminated biomass required	Remaining liability issues, including maintenance for indefinite period of time (containment rather than removal)
Rhizofiltration	Readily absorbs metals	Applicable for treatment of water only
	Potential for metal recovery	Metals are concentrated in plant biomass and must be disposed of eventually

humus rich topsoil. In Stafford et al. (1991), earthworms were not shown to accumulate significant amounts of cadmium from nonforested dredged material in the Times Beach, New York, CPF. However, earthworms in the leaf-littered dredged material beneath volunteer cottonwood trees had significantly elevated cadmium levels, indicating potential transfer to higher levels of the food chain. These types of situations must be considered in the screening and selection process and, if necessary, management strategies developed to minimize risks to the ecosystem. Control of cottonwood trees and replacement with trees, such as red oak, that minimize uptake of metals would be appropriate in the above example.

The processes and considerations for phytoreclamation of dredged material are complicated. A simple, fast-screening tool is currently not available. However, a protocol to determine if phytoreclamation of dredged material would be successful is now being developed. Each dredged material will require that site/application-specific considerations and physical/chemical characteristics be evaluated. In some cases, contaminated, freshwater dredged material may be phytoreclaimed soon after dewatering with little to no modification. In other cases, modifications such as reduction in soluble salts or chemical amendments may be necessary to enhance plant growth or increase the plant availability of a given contaminant.

The plant pathways and phytoreclamation processes for each contaminant class are shown in Table 2, and, as indicated by question marks, some of these processes are not fully understood.

Some dredged material management plans may allow one or more of these processes to occur concurrently or may require the processes to occur sequentially.

Table 2
Description of Phytoreclamation Processes by Contaminant Class

Contaminant Class	Major Plant Pathways	Phytoreclamation Process
Heavy metals	Uptake, Transformation	Extraction, Immobilization, Stabilization
Petroleum hydrocarbons	Degradation, Uptake ?	Degradation, Immobilization, Stabilization
Polychlorinated biphenyls	Degradation ?	Degradation, Immobilization, Stabilization
Pesticides	Uptake, Metabolism	Extraction, Degradation, Stabilization
Organotins	Uptake ?, ?	Degradation, Immobilization, Stabilization
Dioxins	Degradation ?	Degradation, Immobilization, Stabilization
Explosives	Uptake, Metabolism, Degradation	Extraction, Degradation, Stabilization

A FRAMEWORK FOR DETERMINING PHYTORECLAMATION SUITABILITY: Prior to initiating an evaluation of the phytoreclamation framework, it is assumed that the physical and chemical characterizations of the dredged material have been conducted and a determination has been made that the material is not suitable for open-water placement. It is also assumed that the dredged material is contaminated and will require some form of treatment prior to a beneficial use. Available treatment alternatives include bioreclamation (Technical Note DOER-C4), chemoreclamation (soil washing, stabilization, etc.), or phytoreclamation. Once the phytoreclamation alternative is considered, an evaluation can be conducted using currently available testing protocols. A framework for accomplishing the evaluation is shown in Figure 4. The first step is to determine a strategy and set goals to measure success. Will plants be used to reduce contaminant concentrations or reduce contaminant mobility? Will the dredged material be left in place or removed for reuse elsewhere? What is the ultimate use of the dredged material? The answers to these types of questions will dictate what the phytoreclamation goals must be in relation to Federal, State, and local authority criteria or standards.

The next step is to determine the physicochemical characteristics of the dredged material, based on the condition it will be in during the phytoremediation process. These characteristics will determine, in part, the selection of plant species and soil amendments necessary to ensure plant survival and growth. The effects of plant selection and amendments can then be evaluated to select the most suitable combination. These plant/amendment combinations are then evaluated to determine if the set goals of contaminant reduction/stabilization are met. Reclaimed dredged material must then pass biological and chemical evaluation for adverse effects. Failure to meet these goals or avoiding adverse effects criteria may require modification and additional testing of the phytoreclamation process or evaluation through the chemoreclamation or bioreclamation framework. Materials meeting the stated goals and passing the adverse effects criteria are then suitable for beneficial uses.

TESTS FOR ASSESSMENT OF PLANT GROWTH AND EFFECTS OF AMENDMENTS: For purposes of cleanup or stabilization, the physical and chemical characteristics of the dredged material must be determined prior to designing a phytoreclamation project. The recommended tests include contaminant analysis, pH, texture, salinity, total organic carbon, lime requirement, cation exchange capacity, carbon:nitrogen ratio, phosphorus, nitrogen, and potassium, described in WES

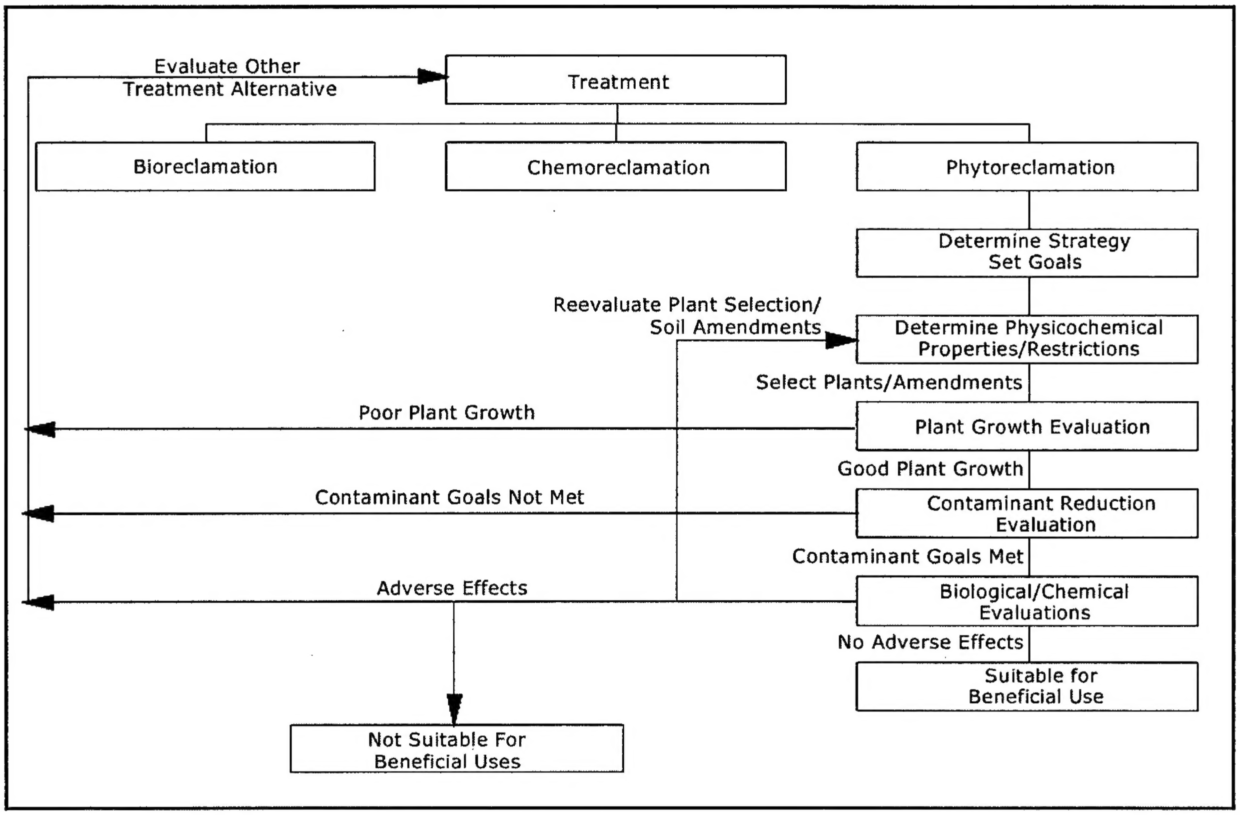

Figure 4. Schematic of the phytoreclamation framework

(1998a). These tests must be conducted on both fresh and aged material, as disturbance, aging, and leaching of a dredged material will likely result in changes to some of the above parameters. There are also chemical extraction tests available to predict uptake of and availability of metals to plants, such as the diethylene triamine pentaacetic acid (DTPA) extraction procedure (Lee, Folsom, and Bates 1983). The physical/chemical properties of some dredged materials may limit the use of phytoreclamation. Excessive salt or contaminants, low or high pH, and other excessively high or low soil parameters may inhibit plant growth. The following procedures are necessary to determine potential for plant growth and survival on dredged material, and additional information is included to assist in the selection of suitable plant species.

- **Aging and Oxidation of Dredged Material.** In most cases, the application of phytoreclamation will occur in an upland condition. The long-term effects of aging and drying of dredged material removed from an aquatic or wetland, anaerobic condition and placed in an upland, aerobic condition may include physical and chemical changes such as reduction in pH and increases in availability of some metals. Changes in physical and chemical properties have previously been predicted on both freshwater and saltwater dredged material (Environmental Laboratory 1987; Lee et al. 1992a,b; 1993; Skogerboe et al. 1987; Skogerboe, Price, and Brandon 1988). These long-term processes can be simulated very quickly in the laboratory and should be performed prior to proceeding with the evaluation process. For freshwater dredged material, the process simply requires air-drying and placing the material in a controlled greenhouse environment for 3 weeks or until the moisture content is reduced to less than 5 percent on an oven-dry weight basis. The material is then ground to pass a

2-mm screen. For saltwater sediments, the process also includes a sediment washing procedure to remove soluble salts. After drying and grinding, the material is placed in 22-L buckets, and reverse osmosis water is added at a ratio of 1:3 sediment to water. The mixture is stirred with an electric stirrer and then allowed to settle. The water is then decanted, and the drying and washing process is repeated two more times. This process usually reduces the soluble salts concentrations to within levels suitable for most freshwater plants and microbes. Another more rapid process involving oven-drying and oxidation with hydrogen peroxide has been developed for predicting the long-term effects of drying and oxidation on surface runoff water quality (WES 1998b) and is being considered as a replacement to the above procedure for the plant tests. High levels of iron sulfides in some dredged materials, such as Blackrock Harbor (Brandon et al. 1991), may result in extremely low pH (<3.0) after the material dries and sulfide is oxidized. Additional tests for these conditions are described in Appendix H of Lee et al. (1985).

- **Determining Plant Suitability Based on Agronomic Characteristics.** Soils and their chemical/physical characteristics vary widely, and even in some of the harshest soil medium, there is a plant that can be established and survive. Selecting the appropriate plant species is the key to establishing plant cover on dredged material. A systematic approach to characterizing problem soil materials and selecting appropriate plant species is provided in an instruction report for problem soils at CE construction sites (Lee et al. 1985). This approach was successfully applied to the revegetation of dredged material for the Field Verification Program CPF at Bridgeport, Connecticut (Brandon et al. 1991). Figure 5 summarizes the various physical and chemical analyses that should be considered in a phased testing approach for dredged material considered for vegetation establishment. Once a dredged material has been fully characterized, the appropriate plant species can be selected according to the characterization results and the geographic location and climate. The vegetation selection guide is provided in Appendix E in Lee et al. (1985), which is available from the authors of this technical note.

  The contaminant characterization will determine the type of phytoreclamation process (Table 2) and the possible plant groups needed for evaluation. Some examples of phytoreclamation demonstrations using various plants to perform various processes are shown in Table 3. Plant species capable of accumulating significant levels of some metals are provided in Table 4. Since the phytoreclamation technology is new and recent developments have focused on certain plant species, the list of plants shown to be successful is limited. However, this information can serve as a guide to the selection of appropriate plant types for further evaluation. Geographic and climatic conditions at the phytoreclamation project site must also be considered to ensure that appropriate plants are selected for the local growing season and climate.

- **Plant Growth in Dredged Material and Effects of Amendments.** Phytoreclamation requires that plants survive on the material in which they are planted. Although the dredged material characterization tests and plant guides described in the previous two sections indicate the potential for plant growth, the singular or combined effects of various contaminants and/or the effects of various amendments may alter this potential. Some useful screening tests for this assessment are described by Sturgis et al. (1999) for both seed germination and plant growth. The tests are designed to compare the effects of various manufactured soil blends, consisting of dredged material and organic waste amendments, on plant biomass yields. For

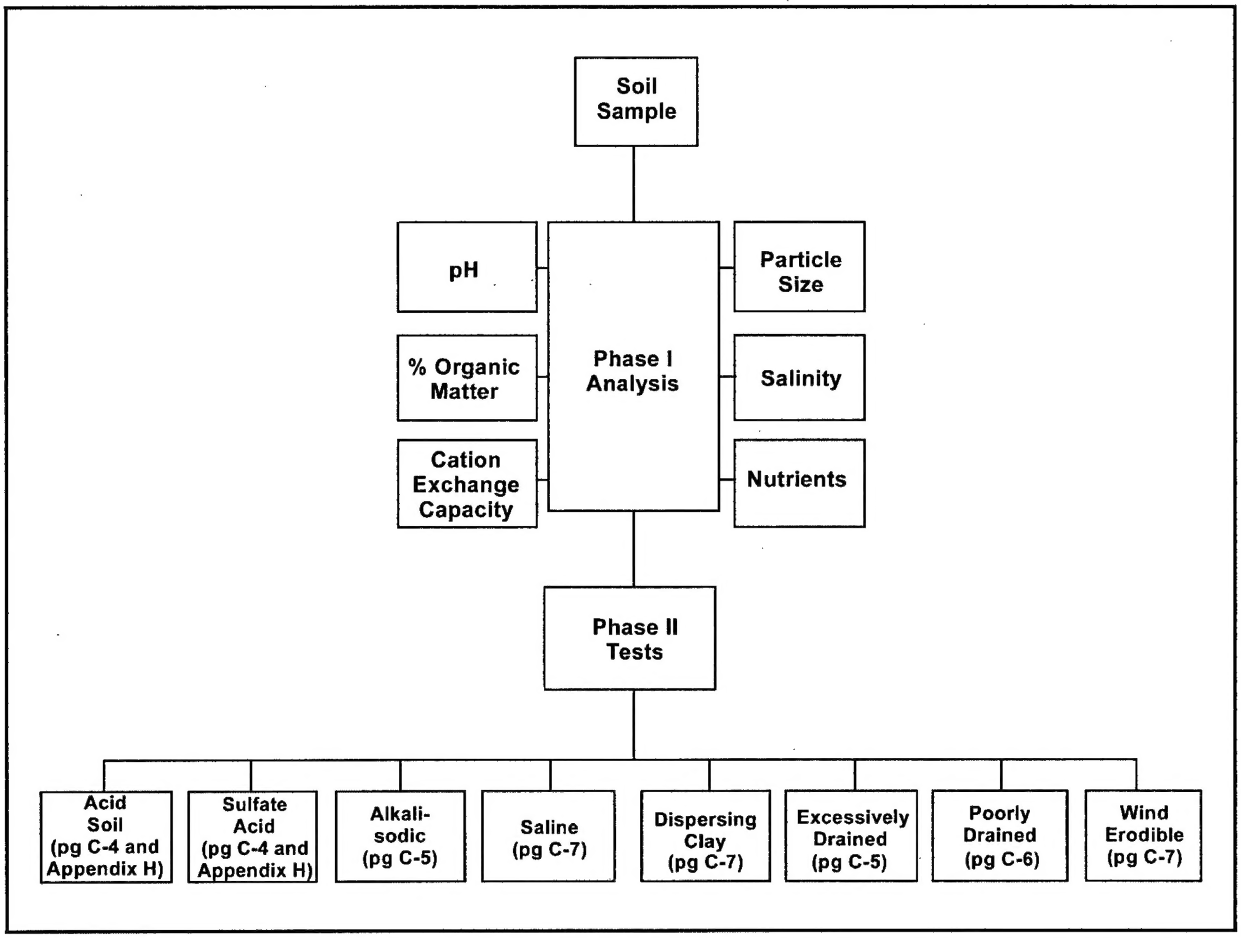

Figure 5. Schematic of physical and chemical analysis of dredged material useful in determining barriers to plant establishment (Lee et al. 1985)

phytoreclamation to work successfully, amendments or pretreatments may be necessary to manipulate the physical and/or chemical characteristics of some dredged materials for optimum results. These manufactured soil screening tests will ensure that plant establishment and adequate growth are attainable. Some dredged materials may contain excessive levels of salt or certain contaminants that inhibit seed germination by restricting water transfer from the material to the seed, resulting in poor germination. Seed germination is evaluated for each plant species on each dredged material in question. Excessive levels of many contaminants may inhibit plant growth either by toxic uptake or by interfering with life-sustaining functions.

For plant growth comparisons, plants are grown in the dredged material or manufactured soil blends in 10-cm nursery containers for 49 days, and the aboveground plant material is harvested and total dry weight biomass is determined. The blend that produces the highest biomass yield is selected for recommendation. These tests will provide an assessment of the growth potential of various plants and amendment combinations.

TESTS FOR EVALUATING PHYTORECLAMATION EFFECTIVENESS: Contaminated dredged material is unique for each dredging location in physical and chemical characteristics.

Table 3
Examples of Sites Demonstrating Phytoreclamation (EPA 1998)

Location	Application	Contaminants	Medium	Plant(s)
Edgewood, MD	Phytovolatilization Rhizofiltration Hydraulic control	Chlorinated solvents	Groundwater	Hybrid poplar
Fort Worth, TX	Phytodegradation Phytovolatilization Rhizofiltration Hydraulic control	Chlorinated solvents	Groundwater	Eastern cottonwood
New Gretna, NJ	Phytodegradation Hydraulic control	Chlorinated solvents	Groundwater	Hybrid poplar
Ogden, UT	Phytoextraction Rhizodegradation	Petroleum Hydrocarbons	Soil Groundwater	Alfalfa Poplar Juniper Fescue
Portsmouth, VA	Phytoextraction Rhizodegradation	Petroleum	Soil	Grasses Clover
Portland, OR	Phytodegradation	PCP PAHs	Soil	Ryegrass
Trenton, NJ	Phytoextraction	Heavy metals Radionuclides	Soil	Indian mustard
Anderson, SC	Phytostabilization	Heavy metals	Soil	Hybrid poplar Grasses
Chernobyl, Ukraine	Rhizofiltration	Radionuclides	Groundwater	Sunflowers
Ashtabula, OH	Rhizofiltration	Radionuclides	Groundwater	Sunflowers
Upton, NY	Phytoextraction	Radionuclides	Soil	Indian mustard Cabbage
Milan, TN	Phytodegradation	Explosives wastes	Groundwater	Duckweed Parrotfeather
Beaverton, OR	Vegetative cover	Metals Nitrates BOD	Not applicable	Cottonwood
Texas City, TX	Vegetative cover	PAHs	Soil	Mulberry
Amana, IA	Riparian corridor Phytodegradation	Nitrates	Groundwater	Hybrid poplar
Southwest OR (Chaney)	Phytoextraction Phytomining	Nickel Cobalt	Soil	*Alyssum murale* *Alyssum corsicum*

Documented successes of phytoreclamation are somewhat limited and are, to date, unlikely to represent conditions found in specific dredged materials. Thus, testing each dredged material is necessary to evaluate the effectiveness of various phytoreclamation techniques. This may include comparing various plant species on contaminant removal/reduction or effects of soil amendments to enhance phytoreclamation. Additional tests may include effects of plants to reduce contaminant movement in surface water runoff. These tests should be conducted using standardized procedures currently used in the assessment of dredged material.

Table 4
Examples of Metal Hyperaccumulator Plants (EPA 1996)

Metal	Plant Species	Metal in Dry Weight of Leaves, %	Native Location
Zinc	*Thlaspi calaminare* *Viola* sp.	<3 1	Germany Europe
Copper	*Aeolanthus biformifolius*	1	Zaire
Nickel	*Phyllanthus serpentinus* *Alyssum bertoloni* and 50 other species of *alyssum* *Sebertia acuminata* *Stackhousia tryonii*	3.8 >3 25 (in latex) 4.1	New Caledonia Southern Europe and Turkey New Caledonia Australia
Lead	*Brassica juncea*	<3.5	India
Cobalt	*Haumaniastrum robertii*	1	Zaire
Selenium	*Asstragalus* sp.	>1	Wyoming*

* Personal Communication, March 1999, Rufus Chaney.

Figure 6. Schematic of WES plant bioassay apparatus

- **Assessment of Plant Uptake/Degradation of Contaminants.** The fate of many contaminants, except for some metals, in vegetation growing on dredged material is not well understood. Previous testing of contaminants in plant tissues was conducted prior to analytical chemistry developments that either provide for plant tissue analysis or detection capabilities low enough for plant analysis. As a result, limited information is available to determine the fate of many contaminants in plants. Consequently, testing on a case-by-case basis is still necessary. A plant bioassay test (Folsom and Price 1989) and American Society for Testing and Materials (ASTM) Standard Method (ASTM 1996) are used to determine contaminant uptake by plants grown in freshwater dredged material (Figure 6). The plant bioassay procedure is a 45-day test from planting to harvest of plant

tissue. It utilizes the plant *Cyperus esculentus* as an indicator crop and can be related to other crops for heavy-metal uptake (van Driel, Smilde, and van Luit 1985). A test for estuarine dredged material using *Sporobolus virginicus* and *Spartina alterniflora* is described by Lee et al. (1992a, 1995) and has been used to evaluate contaminant mobility into plants from a number of saltwater dredged materials. However, for reclaimed saltwater dredged material to be used beneficially, the soluble salts must be removed, and freshwater plants should be used in the evaluation. The plant bioassay can be used to determine the potential for plant growth and uptake of contaminants under simulated field conditions. The plant bioassay test can be used to determine potential for plant uptake of contaminants by harvesting and analysis of the plant tissues of the test plant. For purposes of determining effective phytoreclamation by removal, the total uptake (tissue concentration × total plant weight) on a dry weight basis should be used. Other plant-associated processes (transpiration and plant-associated microbial degradation, etc.) can be determined by comparing preplant and postharvest contaminant concentrations in the dredged material with a nonvegetated dredged material control.

- **Effects of Physical/Chemical Amendments and Plant Selection on Phytoreclamation**. As previously described, the influence of physical and chemical conditions of dredged material will determine the effectiveness of any phytoreclamation effort. There is a fine line between availability of nutrients for growth and uptake of contaminants or activity of other plant-associated processes related to phytoreclamation. Although a contaminant can be made more or less available through soil amendments, the conditions thus created may not be favorable to plant growth. The addition of bulking agents, such as sand or organic matter will not only affect the net concentration of contaminants in a dredged material but can also affect contaminant uptake by plants. The ability of a particular plant to effectively remove a particular contaminant from a soil material is dependent on a number of factors including uptake, total plant biomass, and effects by other contaminants. Some of these issues are addressed in a study by Price et al. (1997). Plant bioassays were conducted on explosives contaminated soil to determine the effects of plant selection, soil type, and soil amendments on uptake of explosives by plants. The soil contained high levels of TNT and RDX at a ratio of 3 to 1 plus degradation products at trace levels. Although TNT was not found in any of the plant tissues tested, plant RDX concentrations were significantly increased as soil clay content was decreased (Figure 7), and the addition of cow manure significantly reduced the plant RDX concentration in the lower clay soils (Figure 8). Aboveground tissue concentrations of RDX were in the order of lettuce > nutsedge > corn (Figure 9) with lettuce concentrations as much as 2 orders of magnitude higher. However, as shown in Figure 10, total RDX removal (concentration × dry weight biomass) was in the order of lettuce > corn > nutsedge. Figure 10 also shows the effects of soil concentration on total uptake. Total uptake was reduced in the 50.3-mg kg^{-1} soil as a result of significantly reduced growth. All plants died in the 667-mg kg^{-1} soil. The TNT was more likely responsible for the reduction in plant growth. However, this was not determined.

  The plant bioassay procedure (Folsom and Price 1989) can be used to determine effective use of chemical and physical amendments (lime, chelates, organic wastes, etc.) to alter contaminant availability and enhance plant uptake or to screen plant species. The selection of amendments, if needed, should be determined from the physical/chemical characteristic test results and the intended phytoreclamation process selected. Various plant/soil amendment combinations can be evaluated to determine the optimum combination to reach specific

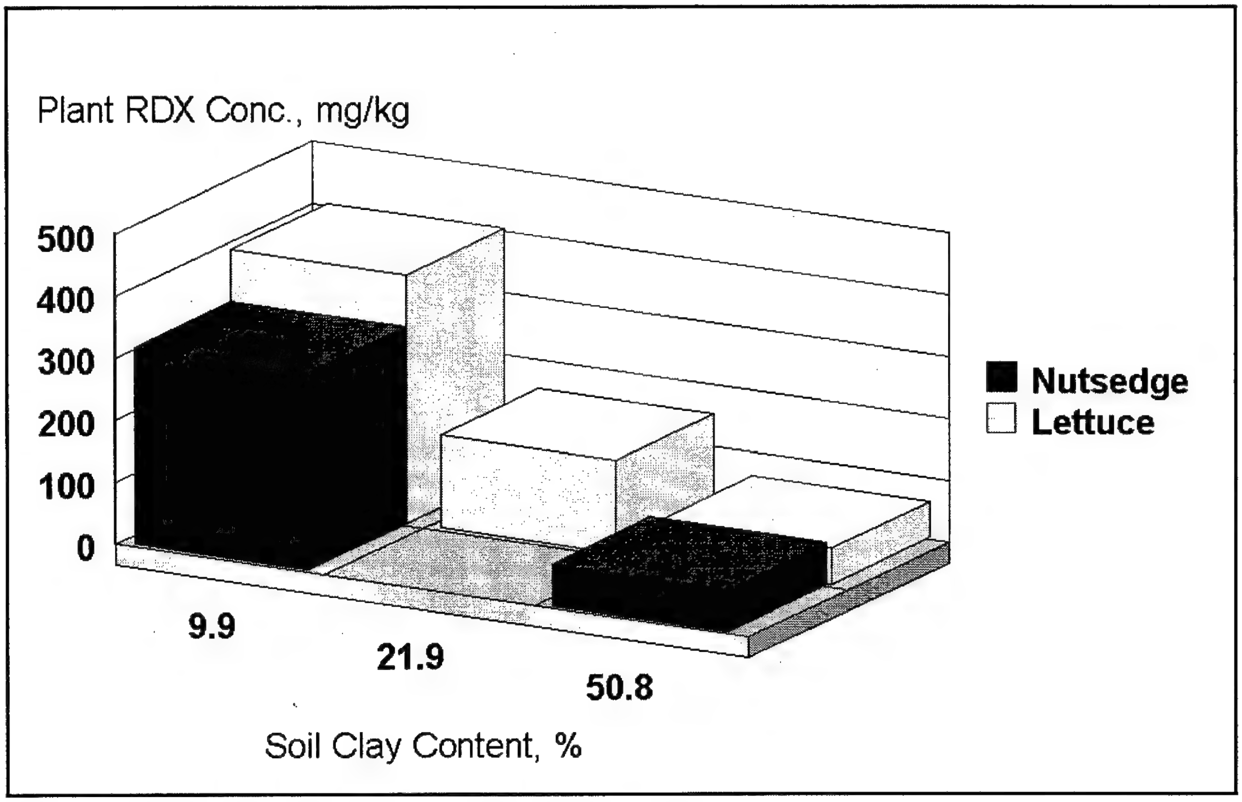

Figure 7. Effect of soil clay content on plant uptake of RDX

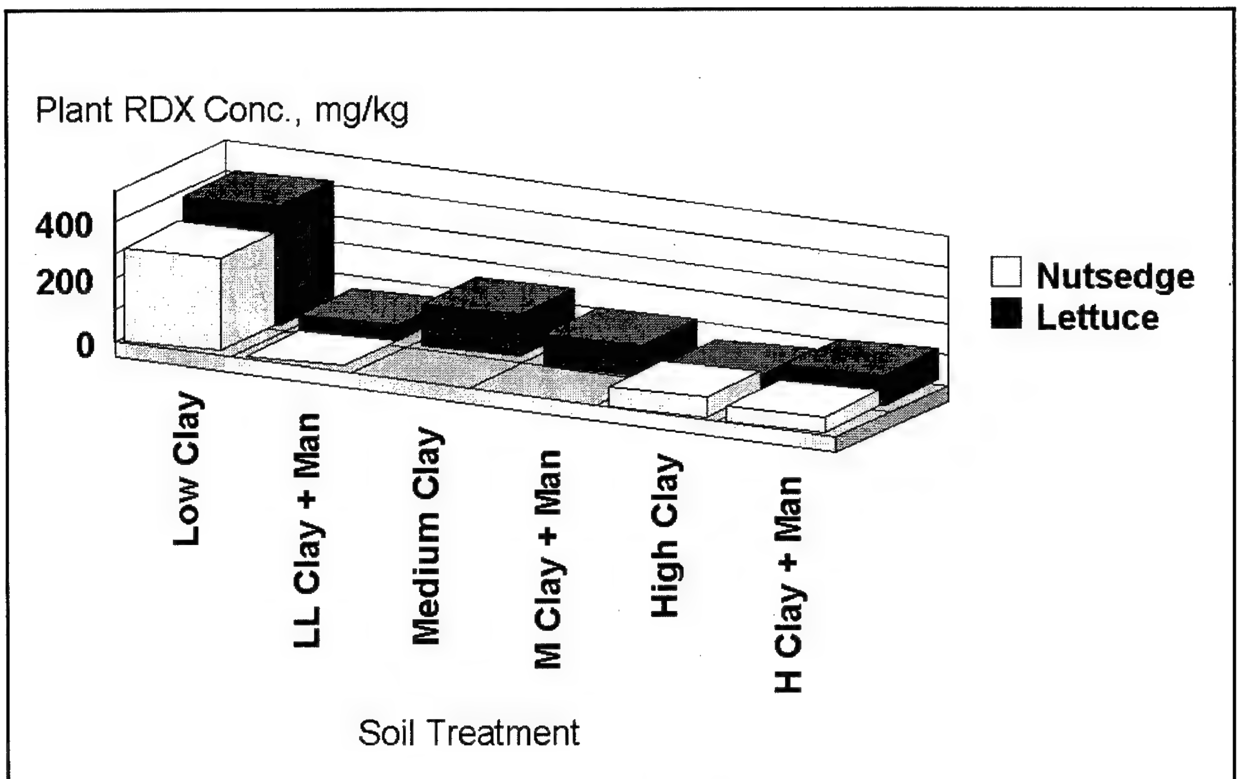

Figure 8. Effect of cow manure amendments on plant uptake of RDX

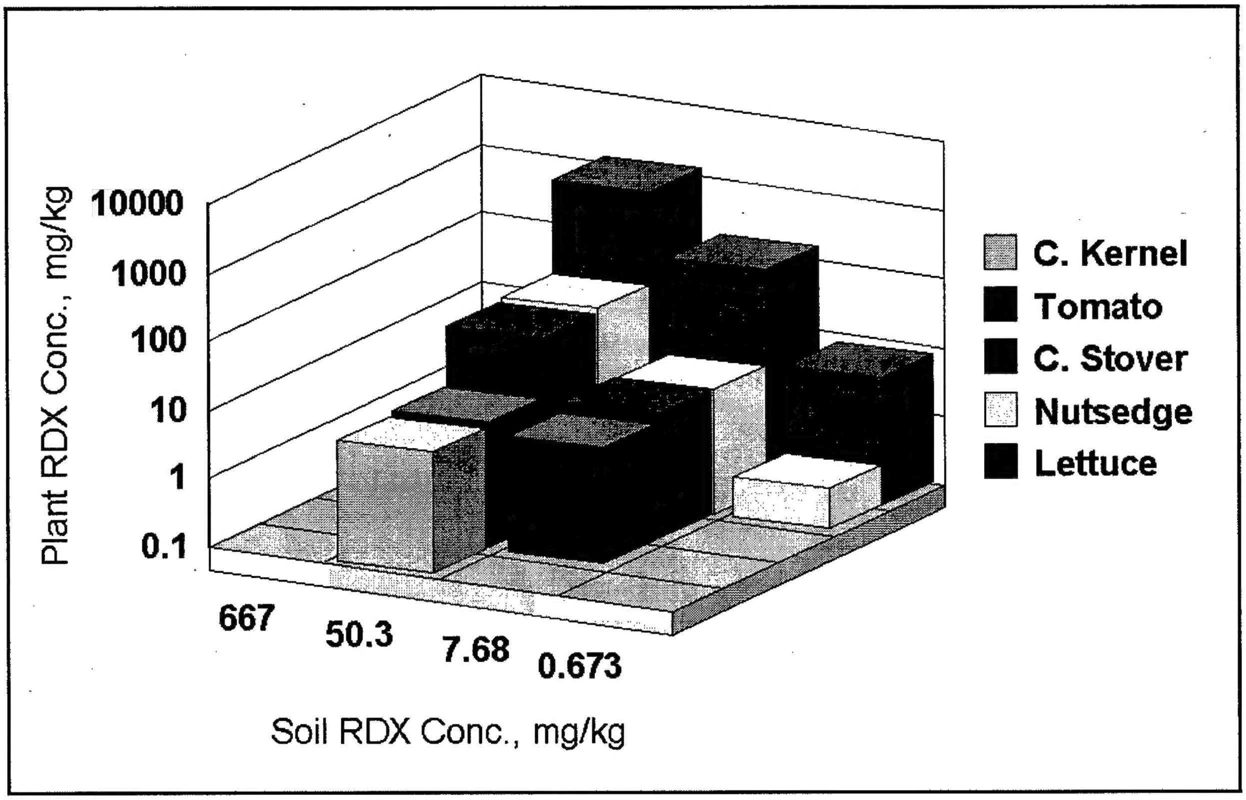

Figure 9. Comparison of plant RDX concentrations

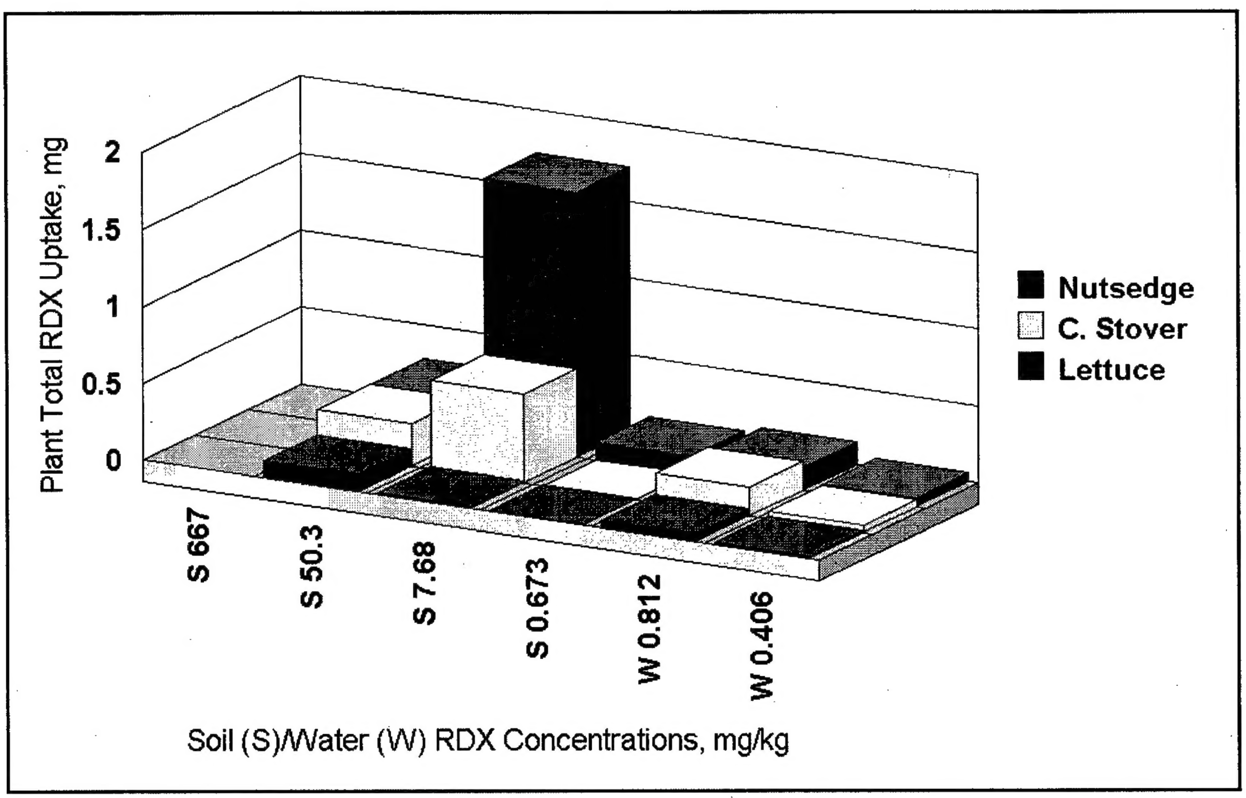

Figure 10. Comparison of total RDX uptake by selected plants

phytoreclamation goals. The plant bioassay procedure requires growing the plants to maturity, generally 45 to 90 days, and chemical analysis for the contaminants of concern.

- **Reduction of Contaminant Releases in Surface Runoff Water.** Rainfall on unprotected dredged material can result in the release of both soluble and insoluble (bound-to-soil particles) contaminants in the surface water runoff. Phytoreclamation through stabilization of the soil surface can reduce the entrainment of sediment into runoff and bound contaminants, while immobilization (chemical and/or physical fixation) will reduce the soluble contaminants. Although there are no specific tests described for upland plants, tests similar to those described by Best et al. (1997a,b,c) for aquatic and wetland plants may be useful in screening upland plants for reduction of soluble contaminants in surface water runoff. Tests using the WES rainfall simulator/lysimeter system (RSLS) can quantify the effectiveness of the selected phytoreclamation process in reducing contaminant movement in surface runoff water. The RSLS has the ability to predict surface runoff water quality from dredged material and other soil materials under various conditions (slope, amendments, vegetation type and condition) and treatment scenarios. Recent unpublished tests at WES (Price, Larson, and Neumann, in preparation) quantified the effectiveness of soil amendments and vegetation in reducing suspended solids and RDX and TNT concentrations in surface runoff from an explosives-contaminated soil. A procedure using the RSLS is currently being developed to evaluate the fate of contaminants in upland/wetland ecosystems, such as an upland CPF and wetland discharge/mixing zones, and can quantify the effectiveness of a phytoreclamation technique in similar situations.

SUMMARY AND CONCLUSIONS: The purpose of this technical note is to describe a developing framework for evaluating the suitability of dredged material for phytoreclamation using currently available testing protocols. Phytoreclamation of dredged material is an attractive treatment alternative that at present has little research support to implement without testing on a case-by-case basis. As research in this area continues, the framework will evolve with the development of simple screening-type tests.

The approaches described in this technical note will assist in determining the feasibility of using phytoreclamation for cleanup or stabilization of contaminated dredged material in order to minimize risks to the environment and to make the material available for beneficial uses. Once a phytoreclamation approach has been determined, implementation and management strategies must be developed to ensure success. The use of phytoreclamation can result in significant cost savings compared with other treatment or stabilization techniques. However, failure to conduct adequate testing and relying on generalities may result in failure of the phytoreclamation effort and/or adverse effects and unacceptable risks to human and environmental concerns.

A number of test procedures and guides from CE reports are cited in this technical note. Subsequent technical notes will follow describing these test procedures in detail.

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> Price, R. A., and Lee, C. R. (1999). "Evaluation of dredged material for phytoreclamation suitability," *DOER Technical Notes Collection* (TN DOER-C3), U.S. Army Engineer Research and Development Center, Vicksburg, MS. *www.wes.army.mil/el/dots/doer*

REFERENCES:

American Society for Testing and Materials. (1996). *Annual book of ASTM standards*. Philadelphia, PA.

Best, E. P. H., Zappi, M. E., Fredrickson, H. L., Sprecher, S. L., Larson, S. L., and Miller, J. L. (1997a). "Screening of aquatic and wetland plant species for phytoremediation of explosives-contaminated groundwater from the Iowa Army Ammunition Plant," Technical Report EL-97-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Best, E. P. H., Sprecher, S. L., Fredrickson, H. L., Zappi, M. E., and Larson, S. L. (1997b). "Screening submersed plant species for phytoremediation of explosives-contaminated groundwater from the Milan Army Ammunition Plant, Milan, Tennessee," Technical Report EL-97-24, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Best, E. P. H., Zappi, M. E., Fredrickson, H. L., Sprecher, S. L., Larson, S. L., and Ochman, M. (1997c). "Screening of aquatic and wetland plant species for phytoremediation of explosives-contaminated groundwater from the Iowa Army Ammunition Plant," *Ann. N.Y. Sci.* 829, 179-194.

Brandon, D. L., Lee, C. R., Skogerboe, J. G., and Wilhelm, G. S. (1991). "Long-term evaluation of plants and animals colonizing contaminated estuarine dredged material placed in both wetland and upland environments," Miscellaneous Paper D-91-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Cunningham, S. D., and Lee, C. R. (1995). "Phytoremediation: Plant-based remediation of contaminated soils and sediments." *Bioremediation: Science and applications*. Soil Science Society of America, Special Publication 43, 145-156.

Environmental Laboratory. (1987). "Disposal alternatives for PCB-contaminated sediments from Indiana Harbor, Indiana; Vol I: Main report," Miscellaneous Paper EL-87-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Folsom, B. L., Jr., and Price, R. A. (1989). "A plant bioassay for assessing plant uptake of heavy metals from contaminated freshwater dredged material," Technical Note EEDP-04-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lee, C. R., Skogerboe, J. G., Eskew, K., Price, R. A., Page, N., et al. (1985). "Restoration of problem soil materials at Corps of Engineers construction sites," Instruction Report EL-85-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lee, C. R., Folsom, B. L., Jr., and Bates, D. J. (1983). "Prediction of plant uptake of toxic metals using a modified DTPA soil extraction," *Sci. Total Environ.* 28,191-202.

Lee, C. R., Tatem, H. E., Simmers, J. W., Skogerboe, J. G., Folsom, B. L., Jr., Price, R. A., Brannon, J. M., Brandon, D. L., Averett, D. E., and Palermo, M. R. (1992a). "Evaluation of upland disposal of Oakland Harbor, California, sediment; Volume I: Turning basin sediments," Miscellaneous Paper EL-92-12, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lee, C. R., Brandon, D. L., Tatem, H. E., Simmers, J. W., Skogerboe, J. G., Price, R. A., Brannon, J. M., Myers, T. E., and Palermo, M. R. (1992b). "Evaluation of upland disposal of J. F. Baldwin Ship Channel sediment," Miscellaneous Paper EL-92-17, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lee, C. R., Brandon, D. L., Tatem, H. E., Simmers, J. W., Skogerboe, J. G., Price, R. A., Brannon, J. M., Myers, T. E., and Palermo, M. R. (1993). "Evaluation of upland disposal of Oakland Harbor, California, sediment; Volume II: Inner and outer harbor sediments," Miscellaneous Paper EL-92-12, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lee, C. R., Simmers, J. W., Price, R. A., Brandon, D. L., and Tatem, H. E. (1995). "Evaluation of wetland creation with John F. Baldwin Ship Channel sediment," Final Draft, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Price, R. A., Larson, S. L., and Neumann, R. D. "Effects of soil amendments and vegetation on the fate of RDX and TNT in soil and surface water runoff," Report in preparation, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Price, R. A., Pennington, J. C., Neumann, D., Hayes, C. A., and Larson, S. L. (1997). "Plant uptake of explosives from contaminated soil and irrigation water at the former Nebraska Ordnance Plant, Mead, Nebraska," Technical Report EL-97-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Skogerboe, J. G., Price, R. A., and Brandon, D. L. (1988). "New Bedford Harbor Superfund Project, Acushnet River Estuary engineering feasibility study of dredging and dredged material disposal alternatives; Report 4, Surface runoff quality evaluation for confined disposal," Technical Report EL-88-15, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Skogerboe, J. G., Lee, C. R., Price, R. A., Brandon, D., and Hollins, G. (1987). "Prediction of surface runoff water quality from Blackrock Harbor dredged material placed in an upland disposal site," Miscellaneous Paper D-87-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Stafford, E. A., Simmers, J. W., Rhett, G. R., and Brown, C. P. (1991). "Interim report: Collation and interpretation of data for Times Beach confined disposal facility, Buffalo, New York," Miscellaneous Paper D-91-17, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Sturgis, T. C., Lee, C. R., Banks, H. C, Jr., and Johnson, K. "Manufactured soil screening test," *DOER Technical Notes Collection* (TN DOER C-6), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

U.S. Army Engineer Waterways Experiment Station. (1998a). "Dredged material characterization tests for beneficial use suitability," Technical Note DOER-C2, Vicksburg, MS.

U.S. Army Engineer Waterways Experiment Station. (1998b). "Predicting surface runoff water quality from the upland disposal of contaminated dredged material," Technical Note EEDP-02-25, Vicksburg, MS.

U.S. Army Environmental Center. (1997). "Phytoremediation of lead," *Innovative technology demonstration, evaluation and transfer activities, FY 96 annual report.* Report No. SFIM-AEC-ET-CR-97013, 82-89.

U.S. Environmental Protection Agency. (1996). "Recent developments for in situ treatment of metal contaminated soils," EPA/542/R-96/008.

U.S. Environmental Protection Agency. (1998). "A citizen's guide to phytoremediation," Technology Fact Sheet, EPA, NCEPI, EPA/542/F-98/011.

van Driel, W., Smilde, K. W., and van Luit, B. (1985). "Comparison of the heavy-metal uptake of *Cyperus esculentus* and of agronomic plants grown on contaminated Dutch sediments," Miscellaneous Paper D-83-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.